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Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: www.tandfonline.com/journals/sagb20

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To cite this article: M. Tähtikarhu & J. Hyväluoma (2026) Exploring the relative importance of subsurface drainage parameters, drainage control schedule, peat thickness and topography on groundwater levels in cultivated peat soils, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 76:1, 2685356, DOI: 10.1080/09064710.2026.2685356

To link to this article: https://doi.org/10.1080/09064710.2026.2685356

Published online: 15 Jul 2026.

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE
2026, VOL. 76, NO. 1, 2685356
https://doi.org/10.1080/09064710.2026.2685356

RAPID COMMUNICATION

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Exploring the relative importance of subsurface drainage parameters, drainage control schedule, peat thickness and topography on groundwater levels in cultivated peat soils

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ABSTRACT

We computationally explored how structurally different factors can control groundwater levels in peat soils. Groundwater levels emerged from the combined impact of different factors. The impact of the factors was in the same order of magnitude. The drainage parameters (median impact -0.22–0.28 m) and terrain slope scenarios (−0.10–0.18 m) affected groundwater levels more than peat thickness (−0.01–0.07 m) in simulations with regular drainage. Drainage control parameters (control depth and schedule) affected groundwater levels more (median impact 0.12–0.32 m) than the drainage parameters (drain depth and spacing, 0.05–0.25 m) in the controlled drainage scenarios. Differences in the control schedule scenarios affected groundwater levels more than the adjustments of the control depth. The impact of controlled drainage was higher in thick (range 0.05–0.45 m) than in thin (0.01–0.33 m) peat soil. The groundwater levels in the different scenarios typically deviated less from each other during the growing seasons (except for the control schedule scenarios and steep upslope conditions), which highlights the challenge of controlling the groundwater levels during growing seasons and the role of the control schedule. Controlled drainage can increase groundwater levels (median ≤0.3 m) in different conditions.

ARTICLE HISTORY
Received 9 February 2026
Accepted 2 June 2026

KEYWORDS
Peat; hydrology; process-based modelling; subdrainage

Highlights

- Groundwater level impacts of drainage and environmental parameters were explored.
- The levels were shown to emerge from combined impacts of different factors.
- It was shown how the impacts often had the same order of magnitude.
- Typically, the parameters affected overall levels more than temporal patterns.

Introduction

Drainage of agricultural land areas is a necessity for efficient crop cultivation in high-latitude conditions and particularly in organic soils. In Finland, approximately 10% of agricultural land is classified as organic (with carbon content >12%), which is mainly under grass (59% of the area) and cereal (39%) production (Wejberg et al. 2024). They produce 50–60% of the greenhouse gas emissions from agriculture (Kekkonen et al. 2019), which highlights their disproportionally large environmental impact. Drainage and related hydrological processes in cultivated peat soils affect the biochemical cycling of the soils with practical implications related to greenhouse gas emission (e.g. Regina et al. 2016). Drainage decreases soil moisture and groundwater level and accelerates peat decomposition, consequently decreasing the soil carbon stocks (e.g. Regina et al., 2016). Water table depth is among the most important factors controlling greenhouse gas emissions from peatlands (e.g. Evans et al. 2021). Optimal water management procedures would provide suitable water table levels for timely implementation of farming operations but would on the other hand, increase

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water levels during the other time periods to decrease environmental loads. Combining these two objectives is a challenge particularly due to the dynamics of the hydrometeorological conditions and spatial heterogeneity of catchment characteristics.

Controlled subsurface drainage provides a method to dynamically adjust the drainage depth (drainage outlet elevation) to different hydrological and seasonal conditions, including efficient drainage during the spring snowmelt periods and decreased drainage efficiency during growing seasons and dry periods. While hydrological impacts of controlled drainage have been previously demonstrated in different mineral soils (Liu et al. 2019; Salo et al. 2021; Youssef et al., 2021), studies in peat soils are limited. Moreover, the related hydrological impacts of different drainage design parameters, different environmental conditions and their relative importance are not well understood. For example, topography (e.g. Mahmood et al. 2023) and peat thickness (Tähtikarhu et al. 2025) can be among the key factors controlling the hydrology in addition to the design parameters such as drain spacing, depth and drainage control schedule (e.g. Turunen et al. 2013; Salo et al. 2021). Also, the role of lateral groundwater fluxes, related to surrounding areas and adjacent open ditches, has been demonstrated previously (Quillet et al. 2017; Liu et al. 2019; Autio et al. 2020; Salo et al. 2021; Lambert et al. 2022; Youssef et al., 2021; Salla et al. 2024). Practically, such fluxes can affect the efficiency of controlled drainage measures (Liu et al. 2019; Youssef et al., 2021; Tähtikarhu et al. 2025). Hydrological impacts of these different factors, and their relative importance, are challenging to disentangle solely from individual field experiments. Computational hydrological models (e.g. Salo et al. 2021; Salla et al. 2022; Youssef et al., 2021) provide means to explore the hydrological implications of different management choices systemically. Such models have been previously applied in peat soils (Autio et al. 2020; Salla et al. 2024). However, the relative impacts of different controlling factors (such as drainage parameters, topography and peat layer thickness) on the capability of controlled drainage to affect groundwater table levels in peat soils have not been compared previously.

The aims of this study were to analyse the impacts and relative importance of subsurface drainage parameters (drain depth, drain spacing and drainage control schedule) and environmental variables (peat layer thickness and topographic conditions) on groundwater level and its dynamics in cultivated peat soils with regular and controlled subsurface drainage. While methodologically, this study focuses on computational exploration, the parameterisation of the model is based on a comprehensive field-scale study in southern Finland (Tähtikarhu et al. 2025). This study extends the previous study (Tähtikarhu et al. 2025) by computationally analysing how a wider range of structurally different key factors can impact groundwater levels.

Materials and methods

The model setup has been calibrated and validated in a previous study at the same experimental field (Tähtikarhu et al. 2025). This study extends the analysis by exploring the groundwater level impacts and relative importance of different subsurface drainage parameters (drain depth, drain spacing and drainage control schedule) and environmental variables (peat layer thickness and topographic conditions) in the cultivated peat soils with regular and controlled subsurface drainage. While the details of the experimental site and the model are presented in Tähtikarhu et al. (2025), they are shortly summarised below.

Experimental site

The site is located in south-western Finland (WGS84: 60°47′19″, 23°32′41″) and consists of 12 plots (area 0.5 ha each) with varying peat layer thickness (0.4 m or 1.2 m from the soil surface) and a flat topography (slope <1%). Forested and gently undulating areas surround the plots. The adjacent forested areas surrounding the experimental plots have mainly higher elevation than the site, inducing a hydrological connection between the plots and the surrounding areas (Tähtikarhu et al. 2025).

The plots are drained either with regular or controlled subsurface drainage. The drains have an inner diameter of 0.05 m and are installed at a depth of 1.1–1.2 m and a drain spacing of 8 m. Drain discharges, groundwater levels and soil moisture values were monitored at the site. Intact soil samples for laboratory measurements of soil water retention and saturated hydraulic conductivity were collected from the site at six depths from topsoil to the depth of 1.25 m. The soil parameters and the hydrological time series were used to parameterise, calibrate and validate the model in a previous study (Tähtikarhu et al. 2025).

This study focused on two experimental plots, which had shallow (depth 0.4 m) and thick (1.2 m) peat layer (see Tähtikarhu et al. 2025 for details).

Model and simulation scenarios

The simulations were conducted with a 3D hydrological model. The purpose of the model is to reasonably describe the dominating hydrological processes and water balance components in the studied site. These components include the flow of water in the soil, subsurface drain discharge, and evapotranspiration. Hydro-meteorological variables (precipitation, potential evapotranspiration and air temperature) are given as input time series, and they drive the hydrological cycle in the model. Previous studies provide a detailed description of the model and the simulation setup for the experimental site (Tähtikarhu and Okkonen 2023; Tähtikarhu et al. 2025). Shortly, the flow of water is described with 3D Richards' equation and is controlled by terrain elevation differences, differences in the hydraulic pressure heads within the domain and soil parameters (hydraulic conductivity and water retention parameters). Unsaturated hydraulic conductivity and water retention are computed with the van Genuchten (1980) model. Subsurface drains are described as sink terms in the model and water flow to the drains is computed with Darcy's law (e.g. Warsta et al. 2013; Tähtikarhu et al. 2025). Controlled subsurface drainage is described by changing the drainage depth according to the control schedule at the site (Salla et al. 2022; Tähtikarhu et al. 2025). Conceptually, the key model features are shown in Figure 1.

This study focused on conducting simulation scenarios based on the calibrated and validated base scenarios (for both thin and thick peat soil plots) of Tähtikarhu et al. (2025). We used three different parameterisations for both thin and thick peat soil, as determined in Tähtikarhu et al. (2025). The simulation period was 1.5 years long (Aug 2021 – Feb 2023). The base scenarios for the thin (peat thickness 0.4 m) and thick (peat thickness 1.2 m) peat areas had a drain depth of 1.1 m and drain spacing of 8 m. Under the controlled drainage base scenario, the drainage control depth was 0.8 m higher than the drain depth (i.e. drainage outlet 0.3 m from the soil surface, Figure 2). Precipitation during the simulation period (600 mm a^{-1}) was

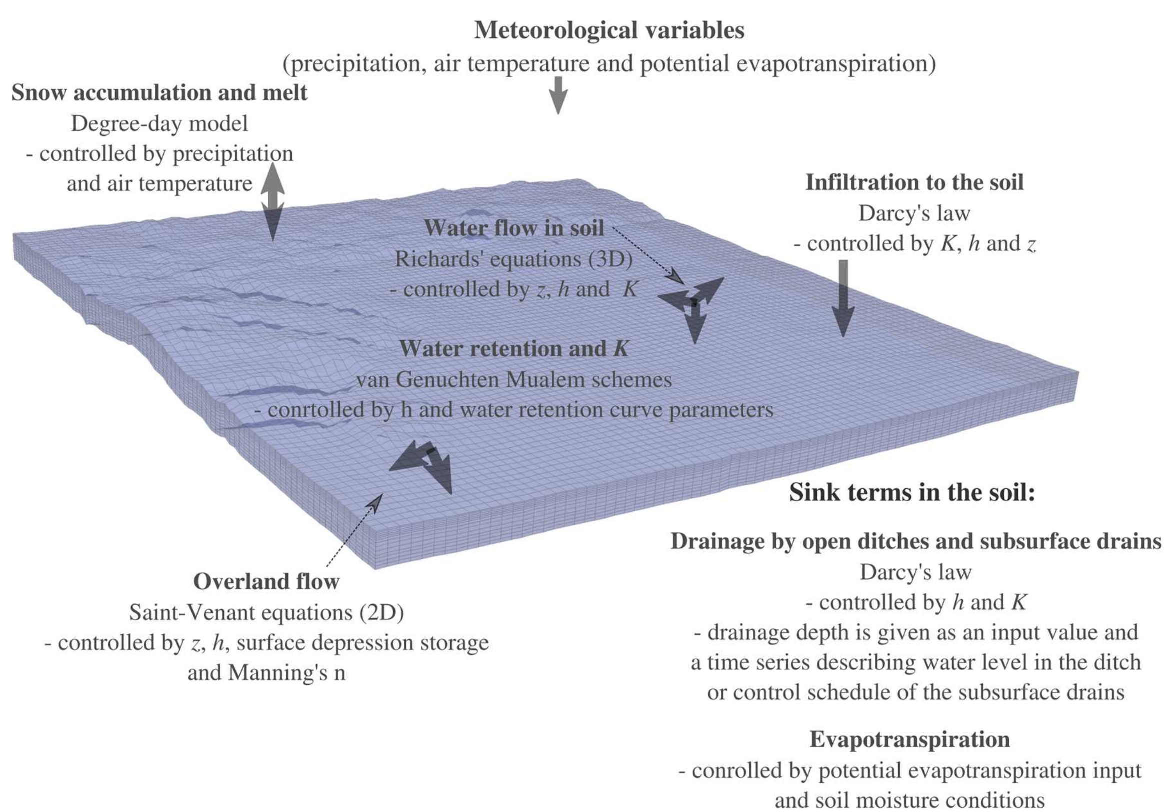

Figure 1. Key processes, parameters and equations of the applied 3D model solution. K = hydraulic conductivity, h = hydraulic pressure head and z = elevation (Tähtikarhu et al. 2025).

comparable to the long-term mean precipitation (2003–2023) of 630 mm a^{-1} (standard deviation 95 mm a^{-1}) at a nearby observatory (Jokioinen observatory of Finnish Meteorological Institute). During the studied summer seasons (Jun-Aug), the mean precipitation (230 mm) and monthly air temperature (16 °C) were close to the long-term averages of precipitation (210 mm, standard deviation 56 mm) and air temperature (16 °C, standard deviation 1 °C). This demonstrates that the simulation period was meteorologically rather close to the local average.

The simulation scenario types were (1) drainage parameters (4 different scenarios), (2) drainage control schedule (four different scenarios), (3) topography (two different scenarios) and (4) peat thickness (two different scenarios). The scenarios and the related parameters are listed in Table 1. The scenarios were run with both base scenarios (regular and controlled drainage). Altogether, this resulted in 40 different simulation scenarios. The applied drainage control time series are visualised in Figure 2. The parameter perturbations were broad, and they affect simulations in structurally different ways. Therefore, the approach describes relative and qualitative influence of the factors within limits of plausible and relatively wide variation.

Regarding the simulation results, the focus was on analysing monthly median groundwater levels (median over the groundwater levels within each month) and related impacts of the different scenarios. The focus was considered interesting from the point of view of practical water management decisions, where clear seasonal and interannual differences can be considered more relevant than short-term groundwater table fluctuations.

Table 1. The applied simulation scenarios with the different scenario types, which were all conducted with setup from areas with thin and thick peat soil (i.e. base scenarios and 20 scenarios for both simulated areas resulting into base scenarios and 40 scenarios in total).

	Scenario type	Scenario name	Description
	Base scenario		Base scenario for regular drainage. Drain depth 1.1 m, drain spacing 8 m. Run for both thin (0.4 m) and thick (1.2 m) peat soil.
Regular drainage	Drainage parameters	Drain depth (0.9 m)	Drain depth decreased to 0.9 m.
		Drain depth (1.5 m)	Drain depth increased to 1.5 m.
		Drain spacing (16 m)	Drain spacing decreased to 16 m.
		Drain spacing (4 m)	Drain spacing increased to 4 m.
	Peat thickness	Thin (0.4 m)	Peat thickness 0.4 m.
		Thick (1.2 m)	Peat thickness 1.2 m.
	Topography	Downslope	Steep downslope area: the terrain slope of the regions sloping outwards of the experimental plots was changed to 0.05.
		Upslope	Steep upslope area: the terrain slope of the regions sloping towards the experimental plots was increased to 0.05 at the northside of the area.
	Base scenario		Base scenario for controlled drainage. Drain depth 1.1 m, drain spacing 8 m. Run for both thin (0.4 m) and thick (1.2 m) peat soil. Drainage control depth (outlet) 0.3 m from the soil surface.
Controlled drainage	Drainage parameters	Drain depth (0.9 m)	Drain depth decreased to 0.9 m.
		Drain depth (1.5 m)	Drain depth increased to 1.5 m.
		Drain spacing (16 m)	Drain spacing increased to 16 m.
		Drain spacing (4 m)	Drain spacing decreased to 4 m.
	Drainage control	Control depth (0.6 m)	Drainage control depth (outlet) 0.6 m from the soil surface (following the control schedule).
		Control depth (0 m)	Drainage control depth (outlet) 0.0 m from the soil surface (following the control schedule).
		Schedule (always on)	Drainage control always on (depth at the base scenario control depth level, i.e. 0.3 m from the soil surface).
		Schedule (half)	Drainage depth at the drain depth (1.1 m from the soil surface) only half of the time compared to the base scenario.
	Peat thickness	Thin (0.4 m)	Peat thickness 0.4 m.
		Thick (1.2 m)	Peat thickness 1.2 m.
	Topography	Downslope	Steep downslope area: the terrain slope of the regions sloping outwards of the experimental plots was changed to 0.05.
		Upslope	Steep upslope area: the terrain slope of the regions sloping towards the experimental plots was increased to 0.05 at the northside of the area.

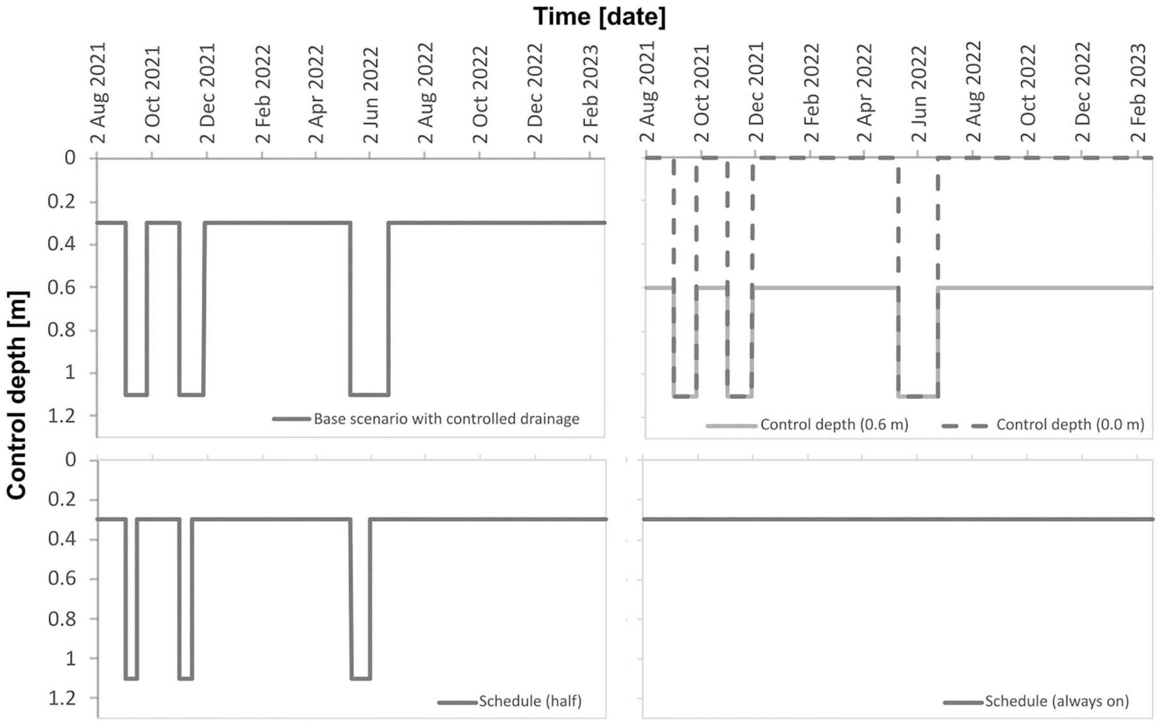

Figure 2. The four different drainage control time series (drainage outlet depth from the soil surface) applied in the modelling scenarios. The depth of the subsurface drain pipes was 1.1 m. See Table 1 for a conceptual description of the different control scenarios.

Results and discussion

In the different scenarios with regular drainage, the groundwater levels varied significantly but had similarities in terms of seasonal variation (Figure 3a,b). The drainage parameters (median impact on groundwater level −0.22 … 0.28 m) and terrain slope scenarios (−0.10 … 0.18 m) affected groundwater level more than peat thickness (−0.01 … 0.07 m) in the simulations (Table 2, Figure 3c,e). The impacts had temporal variability, but most scenarios systematically either increased or decreased groundwater levels throughout the simulation periods (Table 2 and Figure 3e). Note that the up- and downslope scenarios induced the largest range of impact (Figure 3), which demonstrates how the topography and drainage networks around the plot can affect the hydrology and consequently the controlled drainage impacts. The role of lateral groundwater flow and different hydrogeological structures in peatlands have been shown in previous studies (Quillet et al. 2017; Autio et al. 2020; Lambert et al. 2022; Salla et al. 2024), but the implications for cultivated drained peatlands have not been previously compared with varying controlling factors. Based on our simulations, topographic characteristics can have a large impact on groundwater levels in cultivated peat soils, and the magnitude is higher but comparable to changes in the drainage parameters. Differences in peat thickness either increased or decreased groundwater levels (Figure 3c,e). Previously, Lambert et al. (2022) showed that groundwater levels can be higher in soils with a thick peat layer.

Controlled drainage had the ability to increase groundwater levels, with a median increase of 0.12–0.16 m in thin peat soil and 0.16–0.20 m in thick peat soil (difference between the different scenarios with and without controlled drainage) with the base scenario drainage settings (Figure 3d,f, Table 2). Moreover, there were apparent differences between the impacts of the scenarios. For example, controlled drainage had a slightly lower impact in the drainage parameter scenarios (median impact 0.02 … 0.25 m) than in the drainage control scenarios (0.12 … 0.32 m) (Table 2). Also, controlled drainage affected groundwater levels more in the control schedule scenarios than in the adjustments of the control depth (Table 2). The controlled drainage impact in the terrain topography scenarios was of the same magnitude as in the other scenarios (0.12–0.20 m). The impact was higher in the up- than downslope scenarios (Table 2). All controlled drainage scenarios increased the groundwater level. This was likely due to the fact that typically

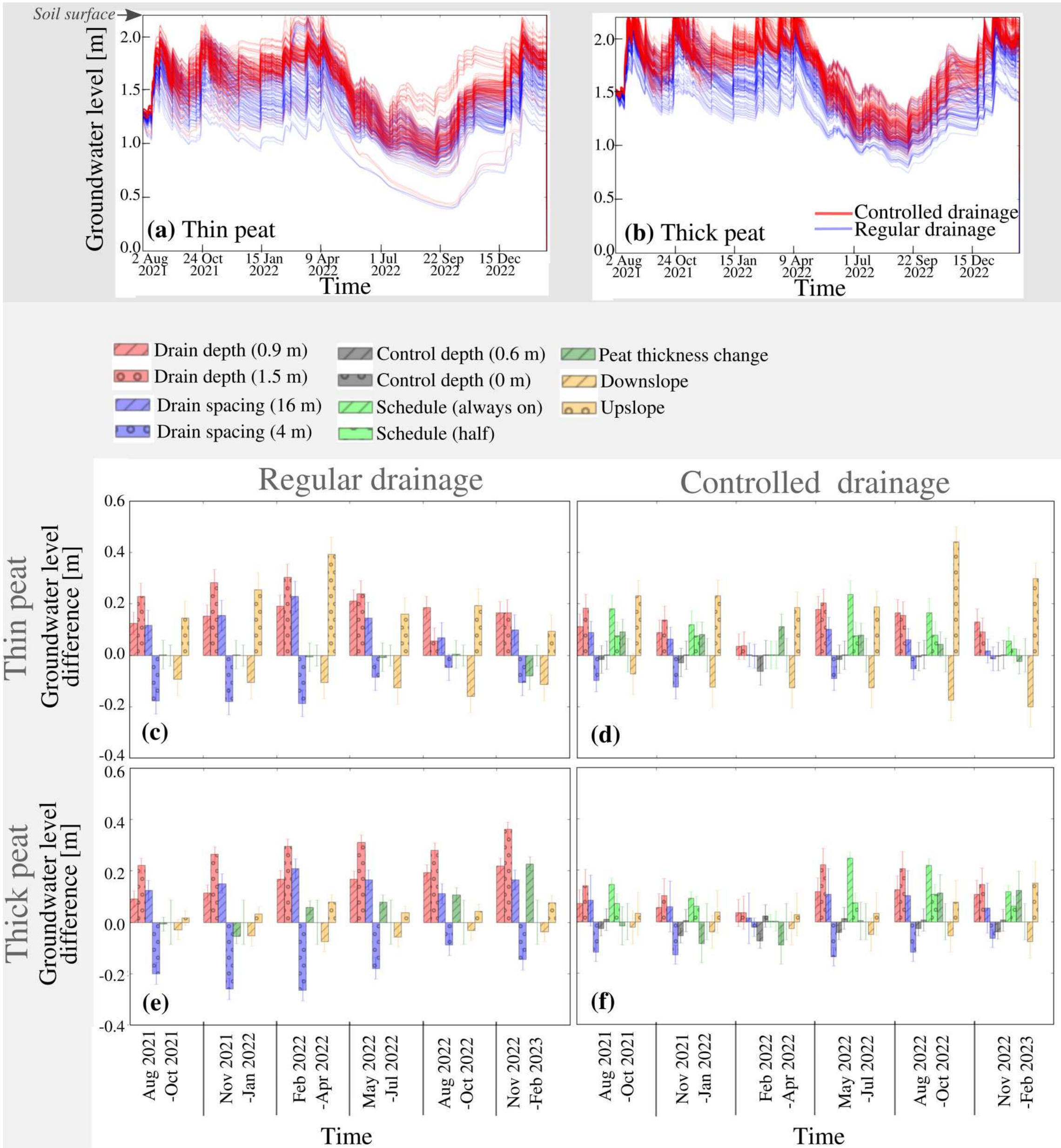

Figure 3. (a-b) Hourly groundwater level with regular and controlled subsurface drainage (all scenarios), and median changes (3-month intervals) in the groundwater level in (c-d) thin and (e-f) thick peat soil with different scenarios (compared to the base scenarios with regular or controlled drainage). Positive values in (c-f) denote increased groundwater level compared to the base scenario and negative values denote decreased level. The whiskers show the standard deviation. Peat thickness change denotes changing thin peat parameters to thick peat parameters in (c-d) and vice versa in (e-f).

(except for the mid-growing seasons) the groundwater level resided above the drainage depth in the scenarios. If the level would be lower, controlled drainage could not have an impact on the groundwater dynamics. Controlled drainage studies in peat soils are rare, but previous studies in mineral and peat soils have shown groundwater level impacts of similar magnitude (Liu et al. 2019; Salo et al. 2021; Youssef et al. 2021; Salla et al. 2024). Controlled drainage can, however, increase lateral groundwater outflow from agricultural fields in mineral soils (Liu et al. 2019; Salo et al. 2021; Youssef et al., 2021) and the lateral flow can even determine the impact of controlled drainage (Tähtikarhu et al. 2025). Peat soils are heterogeneous and anisotropic porous media, which lead to notable differences in horizontal and vertical hydraulic conductivities and thus strongly influence the water movement (Beckwith et al. 2003a, 2003b). Due to lateral flow processes (e.g. Liu et al. 2019; Salo et al. 2021; Youssef et al., 2021) the impact of controlled

Table 2. Median, standard deviation (std), minimum (min) and maximum (max) of the monthly groundwater level differences between the different simulation scenarios. Positive values denote increased groundwater level and negative values denote decreased level.

			Groundwater level difference [m]							
			Thin peat				Thick peat			
	Scenario type	Scenario name	median	std	min	max	median	std	min	max
Regular drainage (difference to the base scenario)	Drainage parameters	Drain depth (0.9 m)	0.17	0.04	0.06	0.22	0.17	0.05	0.05	0.24
		Drain depth (1.5 m)	0.24	0.10	0.02	0.32	0.28	0.08	0.07	0.47
		Drain spacing (16 m)	0.14	0.06	0.02	0.25	0.15	0.04	0.04	0.22
		Drain spacing (4 m)	−0.15	0.06	−0.22	−0.04	−0.22	0.08	−0.29	−0.07
	Peat thickness	Thin (0.4 m)					0.07	0.08	−0.09	0.22
		Thick (1.2 m)	−0.01	0.03	−0.08	0.02				
	Topography	Downslope	−0.10	0.04	−0.26	−0.06	−0.05	0.02	−0.08	0.00
		Upslope	0.18	0.10	0.00	0.53	0.05	0.02	0.00	0.10
Controlled drainage (impact compared to regular drainage)	Drainage parameters	Drain depth (0.9 m)	0.09	0.06	0.01	0.18	0.12	0.06	0.03	0.24
		Drain depth (1.5 m)	0.05	0.05	0.00	0.17	0.02	0.02	0.01	0.08
		Drain spacing (16 m)	0.06	0.04	0.00	0.14	0.10	0.06	0.02	0.24
		Drain spacing (4 m)	0.22	0.17	0.02	0.51	0.25	0.17	0.08	0.57
	Drainage control	Control depth (0.6 m)	0.14	0.09	0.02	0.27	0.12	0.08	0.03	0.30
		Control depth (0.0 m)	0.16	0.10	0.03	0.33	0.17	0.10	0.06	0.39
		Schedule (always on)	0.27	0.06	0.07	0.33	0.32	0.09	0.09	0.46
		Schedule (half)	0.20	0.08	0.07	0.33	0.23	0.08	0.09	0.39
	Peat thickness	Thin (0.4 m)	0.16	0.10	0.03	0.33	0.12	0.07	0.01	0.27
		Thick (1.2 m)	0.20	0.13	0.07	0.45	0.16	0.09	0.05	0.38
	Topography	Downslope	0.12	0.09	0.02	0.30	0.17	0.10	0.06	0.40
		Upslope	0.20	0.12	0.03	0.44	0.19	0.10	0.05	0.41
Controlled drainage (difference to the controlled drainage base scenario)	Drainage parameters	Drain depth (0.9 m)	0.09	0.06	0.01	0.19	0.07	0.04	0.00	0.14
		Drain depth (1.5 m)	0.08	0.07	0.00	0.22	0.14	0.08	0.00	0.24
		Drain spacing (16 m)	0.02	0.04	0.00	0.11	0.05	0.04	0.00	0.11
		Drain spacing (4 m)	−0.05	0.05	−0.15	0.00	−0.10	0.05	−0.15	0.00
	Drainage control	Control depth (0.6 m)	−0.02	0.02	−0.07	0.00	−0.04	0.02	−0.10	0.00
		Control depth (0.0 m)	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.04
		Schedule (always on)	0.05	0.09	0.00	0.25	0.13	0.09	0.00	0.26
		Schedule (half)	0.03	0.04	0.00	0.13	0.05	0.05	0.00	0.12
	Peat thickness	Thin (0.4 m)					−0.02	0.10	−0.13	0.25
		Thick (1.2 m)	0.08	0.06	−0.10	0.12				
	Topography	Downslope	−0.12	0.06	−0.28	−0.06	−0.04	0.02	−0.11	0.00
		Upslope	0.22	0.11	0.01	0.47	0.03	0.05	0.00	0.19

drainage can be dependent on factors such as lateral hydraulic conductivity and organisation of related flowpaths in the surrounding areas. However, such an impact is site-specific and does not necessarily have a high impact on the hydrological implications of controlled drainage (Salla et al. 2024). Our results demonstrate the potential role of lateral flow in subdrained cultivated peat soils in varying drainage and environmental settings. Data on hydrogeological characteristics near peatlands of Finland are scarce, which challenges the targeting of controlled drainage measures within landscapes.

In addition to the impacts of controlled drainage on groundwater level (difference between controlled drainage and regular drainage), we also compared the median groundwater levels in different scenarios with the controlled drainage base scenarios. Those drainage parameters, topography and peat thickness scenarios, which decreased the groundwater level in regular drainage scenarios (compared to the base scenario), also had lower groundwater levels in the controlled drainage simulations compared to the controlled drainage base scenarios (Table 2). For example, with the controlled drainage and narrow drain spacing, the groundwater level was lower (median difference −0.05 … −0.10 m) compared to the base scenario with controlled drainage, even though the impact of controlled drainage was relatively high with the narrow drain spacing (0.22–0.25 m). In the topography scenarios with controlled drainage, the groundwater level resided often higher (in the upslope scenarios) or lower (downslope scenarios) than in the other scenarios (Table 2). In the controlled drainage simulations with thin peat soil, groundwater level resided 0.02–0.08 m lower than with the thick peat soils (Table 2). Our results demonstrate how the different factors affect the formation of groundwater levels in cultivated peat soils with a similar magnitude, but with the differences in their relative impact. Note, however, that in addition to peat soil thickness, peat properties and hydrometeorological conditions can vary spatiotemporally. Hydraulic properties of peat soils have been previously mapped in the Nordic countries (Menberu et al. 2021), which provides a basis for understanding the differences and implementing in models, but the implications of the variability regarding field-scale water management is still limited. The physical and hydraulic characteristics of cultivated peat soils strongly depend on the drainage and management history (Kechavarzi et al. 2010; Hyväluoma et al. 2020). Simulation studies would provide a means to investigate the field-scale implications of varying hydraulic properties. The variations in the applied drainage parameters (drain spacing 4–16 m, drain depth 0.9–1.5 m) can be considered relatively wide and thus represent considerable differences in drainage conditions (rather than small adjustments). Furthermore, overall, the studies' parameter perturbations were relatively wide and described the influence of structurally different factors on groundwater levels. Due to the structural differences (e.g. drainage parameters versus topography) the impacts of the parameter variations are not comparable in a direct and absolute way. Rather, they provide insight into their relative impact within wide perturbation ranges in a complex hydrological system.

The impacts of controlled drainage on groundwater levels also differed temporally. As shown in Figure 4, the groundwater level impacts of controlled drainage within the different scenario types typically deviated clearly more during the dormant periods than during the growing season (Jun-Aug). That is, for example, the simulations with the different drainage parameters (regarding the impacts of controlled drainage) were less different from each other from June to August than, for example, from February to April (Figure 4). The exceptions are the controlled drainage schedule scenarios, where the scenarios differed more from each other during the early growing season than during other time periods (Figure 4). This demonstrates the role of the control schedule and the challenge of maintaining a sufficiently low groundwater table level for farming operations during spring and a high groundwater level during the following growing season.

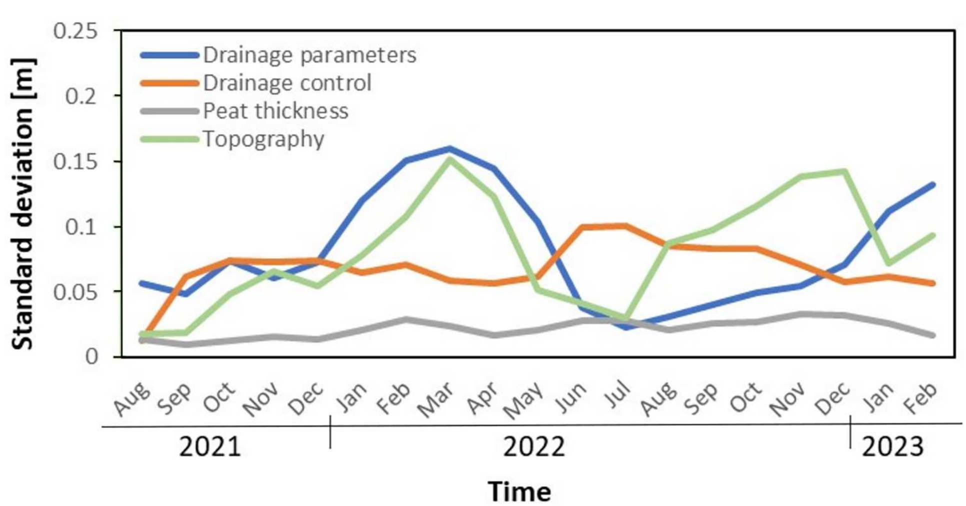

Figure 4. Standard deviations of the monthly median controlled drainage groundwater level impacts (namely differences between the controlled drainage scenario and the base scenario with regular drainage) within each scenario type (peat thickness scenarios include the base scenarios). The deviations demonstrate the temporal differences within the scenario types (for example how much different drainage parameter simulations deviate from each other monthly).

The results suggest that the schedule must be carefully timed to be able to affect growing season groundwater levels. Greenhouse gas emissions are typically the highest during the growing seasons (Berglund and Berglund 2011; Heikkinen et al. 2024; Honkanen et al. 2024). Irrigation combined with controlled drainage would be one option to respond to this challenge, even though the approach could be limited by the local availability of water (e.g. Peltonen-Sainio et al. 2015). Note also that the topographic scenarios deviated relatively much during the growing season, due to the upslope scenario, which increased groundwater influx to the area. The meteorological conditions during the study period were rather close to the local long-term average, and analysing markedly differing hydrometeorological years would be an important future study topic (e.g. Salla et al. 2022).

While the benefit of the model application was to explore the hydrological impacts of a variety of scenarios, the approach also had its limitations. Simulations with a wider variety of hydrometeorological conditions and for example, climate change scenarios would further improve the estimates. Hydrological impacts of parameter variability could be further explored with data from different types of peat soils and hydrogeological structures (e.g. Quillet et al. 2017). Peat soils have a complex dual-porosity structure (Rezanezhad et al. 2016) and a notable proportion of runoff occurs through macropores (Wallage and Holden 2011; Hyväluoma et al. 2020). Therefore, descriptions related to macroporosity could further improve the hydrological description (e.g. Gärdenäs et al. 2006; Salla et al. 2024). We used a constant root depth of 0.5 m in the simulations, which corresponds to observed root depths according to our unpublished data and previous studies (Schwärzel et al., 2006; Berglund, 1996) and the model performance was reasonable (Tähtikarhu et al. 2025). However, root depths and their dynamics can be dependent on the prevailing moisture conditions (e.g. Schwärzel et al., 2006) and plant species (Hoad et al. 2001), and therefore it could be beneficial to study root depths of different plants in the context of peatland drainage. Moisture availability for plant growth can be considered high in peat soils in high-latitude conditions, and in the current study moisture conditions had only a minor impact on evapotranspiration. Previously, a range of different peat soil conceptualisations has been applied in peatland hydrological models (Autio et al. 2020). Our application showed a systems-based method to analyse the hydrological impacts of key factors using model realisations which reasonably align with the overall behaviour of the studied experimental fields (Tähtikarhu et al. 2025). While the process-based framework is a reasonable method to analyse the key factors, it is still clear that there are knowledge gaps regarding the hydrology of peatlands and their modelling (e.g. Tähtikarhu et al. 2025). In this application, the mean absolute difference between simulated and measured groundwater levels was 0.16–0.22 during calibration and validation (Tähtikarhu et al. 2025), which highlights the challenge of accurately describing hydrological dynamics. Despite the differences and uncertainties of different models, overall modelling approaches at different scales can be considered useful in improving systemic understanding of the hydrology of cultivated peat soils.

Conclusions

The formation of groundwater levels in cultivated peat soils arises from a number of factors, and this study shows how they can have an impact of similar magnitude, but with differences in their relative importance. Based on the computational exploration with the 3D hydrological model, controlled drainage can potentially affect groundwater levels under a range of drainage parameters and environmental (peat thickness and topographic) conditions with a similar order of magnitude, but with clear site-specific differences. The impact of controlled drainage can be visible throughout the year, except for the growing season when the groundwater levels are relatively similar in the different scenarios. Growing season groundwater tables can be, however, affected by the choice of control schedule. Control schedule had a higher impact on groundwater levels than adjustments in the control depth, especially during growing seasons. Overall, typically the studied drainage and environmental parameters affected more the level of the groundwater than the temporal patterns of groundwater level variation, with the exception of drainage schedule parameters and topographic variables in thin peat soil scenarios.

The capability of controlled drainage to induce high groundwater table levels can be determined by the lateral flow components. On larger scale, there is currently only limited spatial information available regarding lateral subsurface flow components and related parameters. Based on our exploration, it seems that controlled drainage in cultivated peat soils has the highest potential to increase high groundwater levels in thick peat soils which receive influx of water from surrounding areas. However, it is noteworthy that there can be a wide range of spatial variation in peat soil properties and therefore extending the study to cover also different peat types and hydraulic parameters would likely improve the estimates. Overall, the study quantitatively showed the potential of controlled drainage to control groundwater levels in different conditions and demonstrated that consideration of site-specific differences can be important when siting controlled drainage measures to different locations within landscapes.

Acknowledgements

We acknowledge CSC-IT Center for Science Ltd. for the allocation of computational resources.

Author contributions

CRediT: **M. Tähtikarhu:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **J. Hyväluoma:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was funded by the Ministry of Agriculture and Forestry of Finland (Catch the Carbon research and innovation programme), Drainage Foundation sr. and Suoviljelysyhdistys.

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